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***Abstract*—In this paper, we address opportunistic routing in low-duty cycle wireless sensor networks. A low duty-cycle consists in alternating active and sleep cycles asynchronously in order to save energy. Such a design must take an opportunistic approach in order to cope with the unpredictable appearance of wireless links. In fact, topology-based routing approaches are ineffective in this context. Our main objective is to maximize the network lifespan while guaranteeing i) the routing of packets to the sink and ii) acceptable end-to-end delays, with respect to the needs of military applications as defined in the GETRF project[1]. We propose a new geographical opportunistic cross-layer scheme based on an asynchronous sender-oriented MAC protocol. The proposal sets the priority of selecting the next hop, among all potential candidates, according to its closeness to the sink. The next hop is elected through a selection process based on signalling bursts. The performance evaluation of our proposal is carried out both by an analytical model and simulations. The approach is evaluated in terms of i) probability of packet delivery to the sink, ii) number of hops per path and iii) end-to-end packet delay from the source to the sink.**

Keywords*—*WSN, opportunistic routing, low duty-cycle.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have attracted worldwide attention over the last few years and have led to a wide variety of applications that can cope with harsh operating conditions [1]. WSNs enable communication between several small devices, called sensor nodes, generally deployed in an inaccessible target area, where an infrastructure-based network would be complex, if not impossible. Typically, WSNs are formed by hundreds to thousands of autonomous sensor nodes, which are able to perform self-configuring, self-organizing and/or self-healing. It is worth pointing out that each sensor node is equipped with a small, non-rechargeable battery. The sensor nodes do not necessarily have a direct communication link with a sink, hence routing data is primordial and relies on the multi-hop approach from the source (i.e., the sensor(s) detecting an event) to the final destination (i.e., the sink) [2].

Since sensor nodes are usually deployed in non-accessible areas, maximizing the WSN lifetime is a very important issue. In fact, energy efficiency is considered to be one of the most important key factors in designing reliable WSNs, as stated in seminal works [3] [4] introducing the concept of "low duty-cycling". The main idea behind this approach is to configure the transceivers of sensor nodes to alternate between active and sleep cycles while favoring the sleeping mode as much as possible. Obviously, such a design saves energy by minimizing the occurrence of energy-wasting situations such as overhearing, collisions and traffic overhead generation [5].

In the literature, low duty-cycle MAC protocols can be classified [6] into two categories: i) synchronous and ii) asynchronous. In the first category, synchronous approaches use scheduling to plan common active and sleeping periods for senders and receivers. Unfortunately, this approach is costly in terms of energy consumption since it needs signaling and synchronization stages. In the second category, each sensor node switches **on** and **off** its transceivers independently of the other nodes in the network. The main advantage of this approach is energy efficiency since no extra-messages circulate in the network to guarantee connectivity. However, as each sensor node's on/off activity is independent of its neighbors, routing the packets to the final destination is a highly complex task. In fact, no classical reactive and proactive routing protocols can be exploited since the network topology often changes and is unpredictable. Consequently, routing tables cannot be built in the network. To address this challenge, the solution is to make use of an **opportunistic** routing approach.

In this paper, we propose a new cross-layer geographical opportunistic routing protocol in asynchronous low-duty cycle WSNs. We assume an infrequent event[2] is to be monitored and consequently it is convenient to switch off (i.e., low duty-cycle) the transceivers during part of the network lifetime. Our proposal is based on a sender-initiated MAC protocol,namely `B-MAC` [4]. Note that this work is a part of the GETRF project. We gauge the effectiveness of our proposal in terms of i) probability of packet delivery to the sink, ii) number of hops per path and iii) end-to-end packet delay from the source to the sink. To do so, first we propose an analytical model to evaluate the above metrics. Then, we simulate our proposal by implementing the whole solution and incorporating the slotted-CSMA procedure of IEEE 802.15.4 [7]. The results obtained show that our analytical model matches with simulations and the performances are very satisfactory.

The remainder of this paper is organized as follows. Section II presents the related opportunistic routing protocols. Then, in Section III, we describe our opportunistic routing scheme based on `B-MAC`. The proposed analytical model is detailed in Section IV. In Section V, the simulation settings are presented and the results obtained are analyzed. Finally, Section VI concludes the paper.

II. RELATED WORK

Routing protocols in WSNs [8] are distributed and tend to find the **best** path from a source (i.e., the sensor node(s) detecting the event) to a sink. Routing protocols construct routing-tables and the packets are forwarded according to them. Nevertheless, this routing mechanism is clearly **inefficient** with asynchronous low duty-cycle networks. Given that sensor nodes wake up and sleep asynchronously, the topology becomes highly dynamic, unpredictable and any routing table constructed is doomed to fail. Hence, opportunistic routing

[1]GETRF project is launched by the French National Research Agency in partnership with the Defense Procurement Agency. It targets an efficiently handling transmission in wireless sensor networks.

[2]Intrusion detection, fire detection in forest or industrial plants, etc.

has been identified as a credible solution to overcome this limitation and to avoid overhead caused by topological-based routing protocols, as highlighted in [9]. The opportunistic approach relies on a set of criteria to select the next hop that would forward a packet. Instead of having one fixed next hop, a sensor node has many eligible candidates which can cope with topology variations. For example, a next hop can be selected according to its progression, in terms of reducing the geographical distance towards the sink. The choice of the next hop can be performed **on-the-fly** (e.g., designating the first available neighbor which brings the packet closer to the sink) or through an **election process** (e.g., selecting the closest neighbor to the sink among all the neighbors). Several opportunistic routing protocols have been proposed for wireless ad hoc and sensor networks. Below, we summarize the main geographical and opportunistic protocols found in the literature.

In [10], the location-based protocol called Geographic Random Forwarding (GeRaF) is proposed. A sender defines a list of candidates to forward the packet based on their closeness to the destination. As many candidates are eligible, a busy tone is used to avoid multiple forwarding. In [11], the authors present the ExOR protocol in which the sender indicates in the packet header a list of potential forwarders, each one assigned with a priority. Once the nodes concerned receive the packet, they back-off according to the priority (the higher the priority is, the shorter the delay gets). When the one with the shortest delay initiates the next step of forwarding, the other potential forwarders should discard the packet as soon as they detect a transmission. Hence, redundancy is mitigated. The two protocols are used in a non energy-aware context. In other words, the nodes here are always active and do not switch to a sleeping state at any time.

In [12], the authors introduce the concept of Dynamic Switch-based Forwarding (DSF). The selection of forwarding nodes is based on several criteria: delay, reliability, energy consumption and sleeping schedule. DSF is designed to be used with synchronous low duty-cycle MAC protocols which need an additional overhead related to exchanging sleeping schedules.

In [13], the authors propose a practical opportunistic routing scheme called Opportunistic Routing in Wireless sensor networks (ORW). It assumes asynchronous low duty-cycle MAC protocols and selects the next hop according to a specific metric: Expected Duty-Cycled wakeups (EDC). It takes into account the link quality and the density of the neighbors. In [14], the authors study the ORW protocol and propose Opportunistic Routing In-network Aggregation (ORIA) which is an improved version of ORW supporting in-network aggregation. The protocols proposed in [13] and [14] require the exchange of duty-cycle information to update the EDC metric. These proposals are optimised for heavy traffic conditions.

In [15], a receiver-initiated opportunistic routing cross-layer scheme, based on the `RI-MAC` protocol [16], is proposed. It is interesting as it is quite suitable for light traffic conditions. However, it may have two drawbacks. On the one hand, using beacons (by a potential receiver to request the sender) induces collisions which reduce the delivery rate and increase the number of retransmissions. On the other hand, these beacons make the `RI-MAC` protocol "talkative". Disseminating information in this way can be advantageous to a malicious outsider.

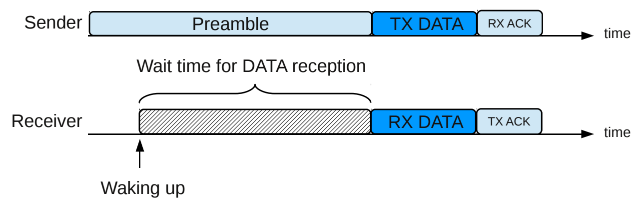


Fig. 1. `B-MAC` communication scheme

In this paper, we are focusing on WSNs monitoring **rare events**. We believe, in this context, that carrying the information from the source to the destination needs to select the best neighbor in terms of geographical distance as detailed in [9]. Also, we mitigate the inconveniences of the receiver-initiated scheme [15]. In the following, we propose a new geographical opportunistic cross-layer scheme based on the sender-initiated MAC protocol namely the `B-MAC` protocol.

III. Opportunistic Routing based on a Sender-Initiated MAC Protocol

In this section, we describe the sender-initiated `B-MAC` protocol and our opportunistic algorithm built on it.

A. B-MAC: Sender-Initiated MAC Protocol

Sender-initiated MAC protocols employ the mechanism of Low Power Listening (LPL) for independent sensors' schedules. In such a configuration, sensor nodes poll the channel asynchronously and periodically. This varies with the length of the sleeping period. To plan a rendezvous between a sender and a receiver, transmissions are preceded by the dissemination of a preamble whose length is longer than the sleeping period and acts as a wake-up signal. Such a setting ensures that a sender and a receiver are both active at the same time. Hence, when a node switches its radio on and detects the preamble, it means that the node may be concerned by a coming data exchange and has to remain awake until the end of the process.

In this paper, we make use of `B-MAC` operating as follows. Each node periodically wakes up to check if there is any activity currently on the wireless channel. If so, the sensor node remains active to receive any incoming packet. When a transmitter has a packet to send, it transmits a preamble with a duration that exceeds the maximum sleeping period. In this way, each node wakes up and sleeps based on its own schedule while the transmitter is able to transmit a packet as illustrated in Fig. 1.

The `B-MAC` protocol is energy efficient under light traffic conditions. In fact, when a sensor node switches on its transceiver, it requires only a very short time interval to sense any channel activity. However, if it detects any activity then the node remains awake, even it is not concerned by the current communication. Hence, if the traffic load in the network is huge, sensor nodes will spend all their time sensing the channel, which is extremly costly in terms of energy. This can be considered as a waste of energy for non-targeted nodes due to overhearing. Since we assume infrequent events, this justifies our choice of `B-MAC`. Another advantage of `B-MAC` is that the network is silent and not talkative. Indeed, sensor nodes transmit only their frames, no beacons are sent in the network. This property can be very important when the WSN

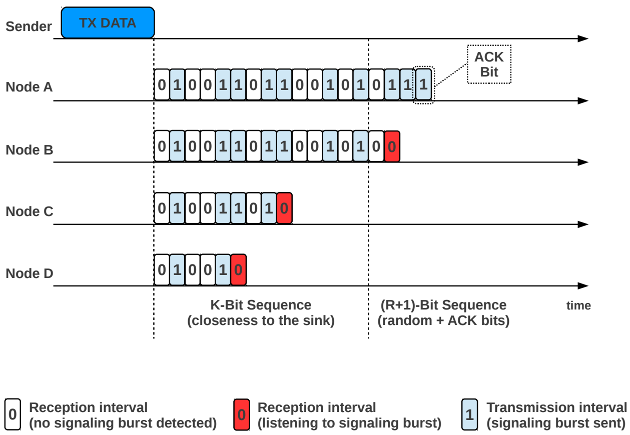


Fig. 2. Burst mode: illustration of election process

is deployed for military applications (as required in GETRF project). Hereafter, we describe how B-MAC can be combined with a geographical opportunistic routing scheme.

B. Geographic opportunistic routing based on B-MAC

When a sensor node $\mathcal{N}$ has a packet to forward to the sink $\mathcal{S}$, it starts by broadcasting a preamble. We suggest that a sender indicates its distance to the sink in this signal and it will be clear why in the following. As the duration of this preamble is at least as long as the maximum sleep cycle, all the neighbors of $\mathcal{N}$ will be able to hear it and know when the packet will be sent as the data is transmitted just after the preamble dissemination. A sender has no previous knowledge about its neighbors or their duty-cycle. Thus, the next hop election process starts at the end of the packet reception. We propose making use of a geographic opportunistic protocol, as in [9]. We assume that sensor nodes hold the information about their location and the location of the sink. In the GETRF project, it is considered that the sensors are manually endowed with these details at the time of the deployment. When all neighboring nodes receive a packet, the election process tends to select the one which most reduces the distance to the sink. The election process is inspired by the signaling bursts with logarithmic coding of the rank [17]. For this reason, we call this approach the "**Burst mode**". This process is a credible solution to the limitations of the preferential backoff of ExOR [11]. In Fig. 2, we illustrate the election of the next hop. During the preamble broadcast, each neighbor $\mathcal{N}_i$ detecting the signal compares its distance to the sink $\mathcal{S}$ with the distance separating the source $\mathcal{N}$ and $\mathcal{S}$. If the neighbor $\mathcal{N}_i$ is closer, it remains active. Otherwise, it switches off its transceiver. Thereby, a subset of neighbors emerges. Each one of these nodes codifies its distance to the sink into a binary sequence and computes its complement to 1. Each bit of this sequence must be long enough to allow the transition from the receiving to the transmission state of vis versa. Then a K-bit code sequence is obtained. Hence, each potential next hop will generate a sequence of bits correlated with the remaining distance to the sink and the closest one to the sink holds the largest bit-sequence. For example, K is equal to 14 in Fig. 2.

Then, potential candidates will examine, sequentially, according to very short periods (of the same order of signal propagation length), the bits of their binary sequence, starting from the most significant bit. If a bit is equal to **1**, the candidate sends a short frame and it is not eliminated from the election. If a bit is equal to **0**, the sensor node senses the medium. If it detects any activity in the medium then there must be a neighbor which is closer to the sink (has a stronger significant bit). Consequently, the sensor node withdraws from the election process and it switches off its transceiver. For example, in Fig. 2, node "D" then node "C" are eliminated at rounds 6 and 9 respectively of the selection process. Otherwise (i.e., no activity), the sensor node concludes that no contender has a signal to send and the possibility of being the winner remains. Once the K bits has been transmitted for all nodes, many potential next-hop nodes may remain. That means that they are all located at the same distance from the sink $\mathcal{S}$. In order to generate only one winner among them, R additional random bits and one bit equal to **1** (placed at the end of the sequence to serve as an acknowledgement) are added. Afterwards, the same election process is carried out. For example, in Fig. 2, we can see that nodes "A" and "B" are located at the same distance from the sink. Hence, the elimination of node "B" occurs during the random R bits ($R = 3$). It is worth noting that the election process is fully distributed. Each node participating in the election does not need to exchange information with its neighbors. Indeed, we can consider the election process as a "battle" between the potential next hops.

We also propose three other variants derived from the **Burst mode** approach. These versions are theoretical and are mainly introduced to be compared with the performance of the **Burst mode**. The first one is the **God mode**. We assume here that there is a centralized entity which knows the position of all potential forwarders and selects the next hop without performing the above election process. The second variant is the **God mode with backtracking**. It is identical to the **God mode** except that if there is no progression towards the sink, the packet is allowed to go into 'reverse gear'. Finally, the last variant that we advance is the **Dijkstra routing mode**. It supposes that a centralized entity has full knowledge of the network graph (independently of the low duty-cycle activity) and applies the shortest path algorithm [18] between the source and the destination. Here, the sender has to transmit the preamble so that the next hop selected by the shortest-path routing remains active after waking up.

IV. ANALYTICAL MODEL

We consider a target deployment area denoted by $\mathcal{A}$. We assume that $\mathcal{A}$ is a square unit area[3]. Sensor nodes are deployed in $\mathcal{A}$ and their positions are the points of a homogeneous Poisson Point Process with density λ. We assume the same communication range throughout the network, denoted by $\mathcal{R}_{com}$. We consider a WSN with an asynchronously low duty-cycle. A sensor node's transceiver is active for **one** time unit and it sleeps for a **constant** period $\frac{1}{\lambda_{off}}$. In order to generate a long path, we assume that a packet is sent from a sensor $\mathcal{O}$ located at $(0.1, 0.1)$ to the sink node $\mathcal{S}$ deployed at $(0.9, 0.9)$ (i.e., diagonal), we note by $\mathcal{D}$ the distance between the source node and the sink.

In what follows, we study the following metrics: the probability of packet delivery, the average number of hops per path, the average packet delay per hop and the average

[3] A scaling factor can be applied to match the figures of a real deployment.

end-to-end packet delay respectively denoted by P_{path}, $\mathcal{N}_{hop}$, T_{hop} and T_{tot}.

We call T_{pk}, T_l and T_s respectively the duration (in time units) of i) the packet ii) the listening period and iii) the selection process of the packet offering the best progress towards the destination. The preamble has a duration of $1/\lambda_{off}$. In this model, we do not consider the contention and collision periods. During the preamble dissemination by a sender, all its neighbors will wake up. The selection process induces a greedy routing in the sender's neighborhood as analyzed in [19]. If we call γ the distance between the current node and the sink, the mean value of the progression towards the sink Pr is:

$$Pr \simeq \mathcal{R}_{com} - \frac{\Gamma(5/3)}{(\lambda a_0)^{2/3}}$$

with $a_0 = \sqrt{\frac{2\mathcal{R}_{com}}{\gamma(\gamma-\mathcal{R}_{com})}\frac{4(\gamma-\mathcal{R}_{com})}{3}}$, (for more details, see [19]). If we assume that $\gamma \gg \mathcal{R}_{com}$, we obtain:

$$a_0 \simeq \frac{4}{3}\sqrt{2\mathcal{R}_{com}}$$

We do not take into account the dependence of Pr with i) the distance to the sink and ii) the dependence between two successive hops (see [19]), thus we obtain:

$$\mathcal{N}_{hop} \simeq \frac{\mathcal{D}}{\mathcal{R}_{com} - \frac{\Gamma(5/3)}{(\frac{4\lambda}{3})^{2/3}(2\mathcal{R}_{com})^{1/3}}}$$

The delay for one hop encompasses the duration of the preamble $1/\lambda_{off}$, the duration of a packet T_{pk} and the duration of the selection process T_s. We obtain:

$$T_{hop} = \frac{1}{\lambda_{off}} + T_{pk} + T_s$$

$$T_{tot} \simeq \mathcal{N}_{hop} \cdot \left(\frac{1}{\lambda_{off}} + T_{pk} + T_s\right)$$

At each hop the probability of having a relay is approximately $(1 - \exp(-\pi\lambda\mathcal{R}_{com}^2))$, we assume that the node is far from the sink and we neglect the dependence between two successive hops. We obtain the probability of reaching the sink:

$$P_{path} \simeq \left(1 - \exp(-\pi\lambda\mathcal{R}_{com}^2)\right)^{\frac{\mathcal{D}}{\mathcal{R}_{com} - \frac{\Gamma(5/3)}{(\frac{4\lambda}{3})^{2/3}(2\mathcal{R}_{com})^{1/3}}}}$$

Now, we compute the energy consumed by a sensor node with and without a low duty-cycle. We recall that a transceiver has four states: i) off, ii) idle, iii) transmission and iv) reception, and respectively it consumes $\mathcal{E}_{off}$, $\mathcal{E}_{idle}$, $\mathcal{E}_{tr}$ and $\mathcal{E}_{rv}$. Assuming the `CC2420` chipset[4], the energy consumption in the different states is: $\mathcal{E}_{off} = 0.06\ mW$, $\mathcal{E}_{idle} = 1.27\ mW$, $\mathcal{E}_{tr} = 52.2\ mW$ and $\mathcal{E}_{rv} = 59.1\ mW$. The nodes wake up with a periodicity of $\frac{1}{\lambda_{off}}$ for a listening period T_l. The power consumed by a node in the stationary mode during a complete cycle is :

$$\mathcal{E}_{bmac}^{on/off} = (\frac{1}{\lambda_{off}} + 1 - T_l) \cdot \mathcal{E}_{off} + T_l \cdot \mathcal{E}_{idle} \quad (1)$$

since during the listening period, the receiver does not receive any signal, `B-MAC` consumes thus $\mathcal{E}_{bmac}^{on/off} = 41.05$ mJ. The additional energy when a packet must be transmitted to the sink is:

$$\mathcal{E}_{bmac}^{p} = \mathcal{N}_{hop} \cdot \left(\frac{\mathcal{E}_{tr}}{\lambda_{off}} + \pi\lambda\mathcal{R}_{com}^2 \cdot (T_l\mathcal{E}_{rv} + \frac{\mathcal{E}_{idle}}{2\lambda_{off}})\right) \quad (2)$$

by developing the above equation, the three terms correspond to the transmission of the preamble (by the transmitter), the reception of the preamble (during T_l) and the idle duration until the end of the preamble (for the potential forwarder). It is very important in `B-MAC` that the potential relays return to the idle state to wait for the end of the preamble, otherwise energy consumption would be even greater than it is. However, we should bear in mind that the protocol we have designed is mostly devoted to the surveillance of very infrequent events. For instance, if $\mathcal{R}_{com} = 0.05$, the consumed energy $\mathcal{E}_{bmac}^{p}$ is equal to $869, 9$ J.

V. Simulation Results

To assess the performance of our proposal, we implemented our discrete-event-based simulator with C++. Each node detecting the monitored event generates a packet to send towards the sink. To do so, the nodes rely on our opportunistic routing scheme. The opportunistic routing and the `B-MAC` protocol properties are implemented in the simulator for each variant described in Section III-B. We also implemented the opportunistic routing variant based on the receiver-initiated protocol `RI-MAC` [15]. Moreover, our implementation takes into consideration slotted CSMA/CA on top of a physical layer with respect to the standard specification of IEEE 802.15.4 [7]. The physical signal propagation model is the two-ray-ground model. It is worth pointing out that we cannot compare our proposal to reactive and proactive routing protocols as they are not suitable in low duty-cycle WSNs (the topology is highly dynamic due to the asynchronous on/off activity and routes cannot be built). The comparison mainly focuses on the performance of the realistic `B-MAC`-based Burst mode, the three non-realistic variants also provided through our proposal, the analytical model and the `RI-MAC`-based opportunistic routing scheme.

A. Simulation Settings

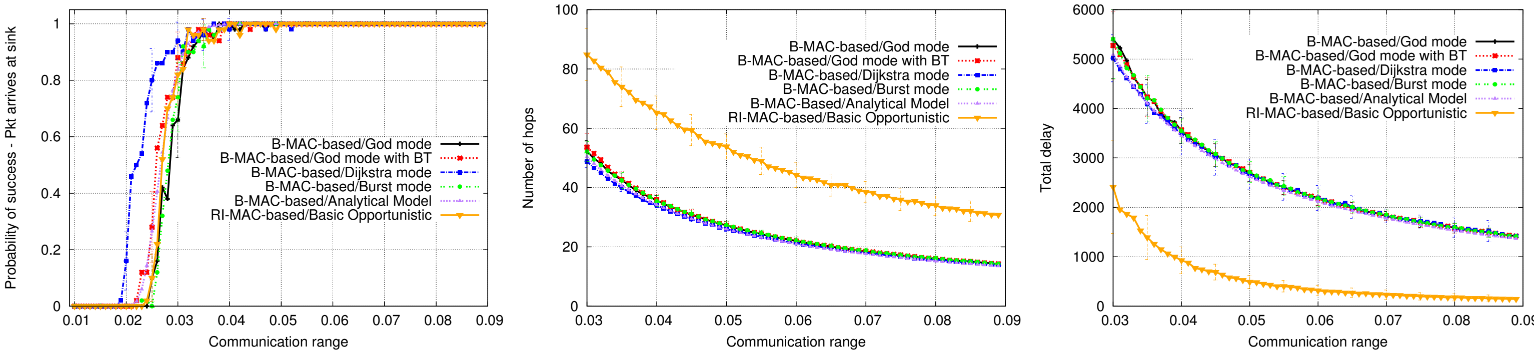
We consider the same target deployment area $\mathcal{A}$ as in Section IV. We assume that the monitored event is located at point $(0.1, 0.1)$. Naturally, it is detected by the sensors that are near enough to it. Each one generates a packet and sends it towards the sink located at $(0.9, 0.9)$. We set the density of sensors λ to 4000 and the density of constant off period λ_{off} to 0.01.

We consider that the sensor nodes use the `CC2420` chipset. The transmit bit rate is equal to 250 $Kbps$ and we assume that the signalling bit in the election process lasts 200 μs in order to accomodate the `CC2420` turnaround times. We define that 1 time unit is equal to 6.1 ms. We set the duration of i) the packet (T_{pk}) and ii) the listening period (T_l) to, respectively 0.7, 0.1 time units. We set K to 14 and R to 3 for the Burst mode hence the duration of selection process is $T_s = 0.56$ time units. For the `RI-MAC`-based scheme, we fix the length of a beacon[5] at 0.1 time unit. We consider that the sensor nodes use the `CC2420` chipset.

We evaluate the probability of delivery P_{path}, the number of hops per path $\mathcal{N}_{hop}$ and the end-to-end packet delay T_{tot} (in time unit) with an average obtained with 50 simulations. Moreover, the results are always presented with error bars corresponding to a confidence level of 95%. It is worth noting that the parameters can be related to large scale deployments by multiplying the distances by 1000, making the network area

[4]https://inst.eecs.berkeley.edu/ cs150/Documents/CC2420.pdf

[5]We assume that the size of the beacon in IEEE 802.15.4 is equal to 19 bytes



(a) Probability of reaching the sink, P_{path} (b) Number of hops, $\mathcal{N}_{hop}$ (c) End-to-end packet delay, T_{tot} in time unit

Fig. 3. Performance evaluation

1 km^2 and the average distance between a node and its closest neighbor approximately 15 m. Finally, we evaluate the energy consumption for both B-MAC and RI-MAC based approaches.

B. *Performance Evaluation*

1) Probability of Packet Delivery P_{path}: In Fig. 3.(a), we evaluate the probability that a packet, generated at the source, reaches the sink. We observe that Dijkstra's shortest path routing offers significantly better results than the opportunistic routing schemes with B-MAC. This can be explained by the fact that Dijkstra's shortest path routing takes into account all the possible routes to the sink whereas the other routing schemes only consider routes built locally with a greedy approach. The opportunistic backtracking variant offers slightly better results than the other opportunistic schemes, especially with low communication ranges. We can also see that the performance provided by the analytical model is strongly comparable to those of the opportunistic B-MAC-based variants.

For the comparison with the receiver-initiated scheme, we have similar results. The use of long preambles greatly reduces the occurrences of collisions with B-MAC-based approaches. By increasing communication ranges, the connectivity between a source and the sink is more likely and the probability of packet delivery obviously tends to 1. For the RI-MAC-based scheme, the collisions can impede a packet progression. Nevertheless, the large number of nodes detecting the event (between 20 and 30 on average) and retransmissions enable the data to reach the sink and make the probability of delivery to also tend to 1.

2) Number of Hops $\mathcal{N}_{hop}$: In Fig. 3.(b), we illustrate the number of hops per path to reach the sink. Focusing on B-MAC-based approaches, we observe that there are no significant differences between the opportunistic routing variants. Moreover, the matching with the analytical model result is very good. Although the Dijkstra mode obviously provides the smallest number of hops, the discrepancy with other modes based on local routing is not very great (always less than 10%). As for the RI-MAC-based scheme, the number of hops is significantly higher as the sender transmits the data to the first detected neighbor which is geographically closer to the sink. It is straightforward to see that our proposal improves the efficiency of delivery by minimizing the number of hops and, thus, mitigating packet lost.

3) End-to-end packet delay T_{tot}: In Fig. 3.(c), we show the end-to-end packet delay to reach the sink (a computation based on the first packet reaching the sink). There are no significant differences between the B-MAC-based routing variants. In addition, the analytical model results match very well. For the RI-MAC-based scheme, the delays are clearly smaller than those obtained by our proposal. Even though the paths with B-MAC-based schemes are shorter, the long preambles induce substantial latency compared with the RI-MAC-based approach. With RI-MAC, latency is expressed by the time needed by the sender to find a neighbor which is closer to the sink, which is much less than the time needed to disseminate a preamble, transmit data and carry out the election process. Nevertheless, the delays obtained by our proposal remain acceptable and meet the needs of the GETRF project.

As we can see, in Fig. 3, we observe that the "Burst mode" proposal exhibits similar performance compared to the "ideal" schemes (i.e., "God mode", "God mode with backtracking" and "Dijkstra routing mode"). This shows that our proposal is suitable to carry out the selection and using it in real deployments is possible.

For all the metrics shown in Fig. 3, we also observe that the simulation results of the opportunistic B-MAC-based variants are very well forecast by the analytical model of B-MAC. This remains true even if, in the simulations, each node detecting the event sends a packet to the sink, whereas in the analytical model, we only have one packet. With the B-MAC preamble, there is no collision and the behaviour of the fastest packet to reach the sink matches the behaviour of the single packet of the analytical model.

4) Energy Consumption: We compare the energy consumption for our proposal and the scheme based on RI-MAC when the system is correctly parametrized (i.e., network connectivity is ensured) by setting $\mathcal{R}_{com}$ to 0.05. We express the energy consumption during i) the forwarding of a packet and ii) the idle state (when no event is detected).

The energy consumed by a sensor node using the RI-MAC low duty-cycle scheme $\mathcal{E}_{rimac}^{on/off}$ for a complete cycle is equal to:

$$\mathcal{E}_{rimac}^{on/off} = \left(\frac{1}{\lambda_{off}} \mathcal{E}_{off} + T_{bc}\mathcal{E}_{tr} + T_{pk}\mathcal{E}_{idle} \right) \quad (3)$$

where T_{bc} is the duration of a beacon which is fixed to 0.1 time unit.

The mean additional energy to convey a packet from a source node to the sink is given by:

$$\mathcal{E}^{p}_{rimac} = \mathcal{N}_{hop} \cdot (T_{pk} + T_{ack}) \cdot (\mathcal{E}_{tr} + \mathcal{E}_{rv}) \quad (4)$$

The value of $\mathcal{N}_{hop}$, here, is expressed in [15].

During the idle state (no event is detected), the opportunistic approach based on B-MAC consumes $\mathcal{E}^{on/off}_{bmac}$ equal to 41.5 mJ (see equation 1) for one cycle of $(\frac{1}{\lambda_{off}} + 1)$ time units, whereas the opportunistic scheme based on RI-MAC consumes $\mathcal{E}^{on/off}_{rimac}$ which is equal to 75.4 mJ (see equation 3). When RI-MAC is considered, the energy consumption is more significant as it relies on the dissemination of beacons. Using B-MAC does not require signaling from a receiver. Therefore, no information is exchanged, in this case. The network remains silent and consumes around 45% less than the RI-MAC-based approach. During the same cycle, a protocol assuming that all nodes are maintained active induces an energy consumption of 782.6 mJ. This is 19 times more than the consumption of the opportunistic approach using B-MAC and 10 times more than the consumption of the opportunistic approach using RI-MAC. This clearly shows the benefit of our proposal in terms of energy consumption.

When an event is a detected, the cost of sending a packet to the sink is $\mathcal{E}^{p}_{bmac} = 869.9$ J for the B-MAC-based scheme (see equation 2). The energy consumption $\mathcal{E}^{p}_{rimac}$ is equal to 36 J for the RI-MAC-based scheme (see equation 4) which is 24 times less, even if the number of hops to reach the sink is less with the B-MAC approach: 30 hops rather than 50 with RI-MAC. This can be explained by the cost introduced by broadcasting long preambles when using B-MAC. Given that the GETRF project targets monitoring infrequent events, using our proposal remains suitable. In fact, it is silent during idle periods which are long and optimizes energy consumption.

5) Summary: we conclude that i) the probability of delivery with our proposal is comparable to the RI-MAC-based scheme (but with fewer collisions), ii) the total delay is much better for the RI-MAC-based opportunistic routing than for the B-MAC-based approach (which remains, nevertheless, acceptable), iii) energy consumption, when no event is reported, is less for the B-MAC-based approach, iv) the energy to convey an alarm packet is much less for the RI-MAC-based opportunistic routing and v) the B-MAC-based approach is silent and the network cannot be detected easily. In contrast RIMAC sends periodic beacons which is not suitable in military applications. Given that we are interested in a military application defined in the GETRF project, the B-MAC-based approach is more convenient and the energy consumption stays competitive due to the infrequent requests.

VI. Conclusion

In this paper, we have presented a new opportunistic routing scheme based on a sender-initiated MAC protocol, namely B-MAC. Such a scheme is proposed for low duty-cycle WSNs. In fact, existing proactive and reactive routing schemes are unsuitable in face of dynamic network topology changes. The routing scheme is an opportunistic greedy approach based on geographical information. Our proposal provides a contribution which matches with the needs of the GETRF project tackling a military application dedicated to monitoring infrequent events. Such an application has to ensure a tradeoff between i) efficient delivery, ii) acceptable end-to-end delay, iii) optimized energy consumption and iv) silent network. The results obtained show that our scheme based on signaling bursts could be used in real scenarios and that it meets the GETRF objectives.

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